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RF PERFORMANCE EVALUATION OF FERROELECTRIC VARACTOR SHUNT SWITCHES

Robert Neidhard, Edward Nykiel, John Ebel, Richard Strawser, Keith Stamper, Mark Calcatera, Rand Biggers, Guru Subramanyam and Faruque Ahamed

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14. ABSTRACT
This paper addresses experimental RF performance evaluation, and electrical parameter extraction of different size ferroelectric varactor shunt switches. The ferroelectric varactor shunt switch operation is based on nonlinear dielectric tunability of a $Ba_{0.6}Sr_{0.4}$ TiO_3 (BST) thin-film sandwiched between two metal layers in the parallel plate configuration. Coplanar waveguide implementation of the varactor shunt switch results in a high speed RF switch, with a simple two-metal layer Si MMIC compatible process on high resistivity Si substrates. Experimental RF performance of the switches show low insertion loss for smaller area devices, with good isolation for larger area devices. To optimize the device design, RF performance of multiple devices were tested, and electrical parameters were extracted. The capacitance of the varactor shunt switches tested were tunable more than 4:1 for bias voltages below 12 V. The switching speed of the devices tested was approximately 43 ns based on the step response measurements.

15. SUBJECT TERMS
Advanced Materials, Ferroelectric varactor, capacitive shunt switch, microwave/millimeterwave switches, coplanar waveguide transmission lines

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RF Performance Evaluation of Ferroelectric Varactor Shunt Switches

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Abstract

This paper addresses experimental RF performance evaluation, and electrical parameter extraction of different size ferroelectric varactor shunt switches. The ferroelectric varactor shunt switch operation is based on nonlinear dielectric tunability of a $Ba_{0.6}Sr_{0.4}TiO_3$ (BST) thin-film sandwiched between two metal layers in the parallel plate configuration. Coplanar waveguide implementation of the varactor shunt switch results in a high speed RF switch, with a simple two-metal layer Si MMIC compatible process on high resistivity Si substrates. Experimental RF performance of the switches show low insertion loss for smaller area devices, with good isolation for larger area devices. To optimize the device design, rf performance of multiple devices were tested, and electrical parameters were extracted. The capacitance of the varactor shunt switches tested were tunable more than 4:1 for bias voltages below 12 V. The switching speed of the devices tested was approximately 43 ns based on the step response measurements.

Key words: Ferroelectric varactor, capacitive shunt switch, microwave/millimeterwave switches, coplanar waveguide transmission lines

1. INTRODUCTION

High K tunable microwave dielectrics such as $Ba_xSr_{(1-x)}TiO_3$ (henceforth BST) are gaining acceptance in microwave integrated circuits due to a large need for tunable/reconfigurable circuits[1-3]. Recent developments on tunable dielectrics have shown that the varactors made of BST ferroelectric thin-films have constant Q through millimeterwave frequencies[4]. Ferroelectric varactors are characterized by fast switching speed, ease of integration with Si MMICs, and have reasonable Q at microwave and millimeterwave frequencies[4]. Recently, our group reported a new varactor shunt switch which is based on the large dielectric tunability of the BST ferroelectric thin-films [5-6]. The varactor shunt switch consists of a CPW transmission line loaded by a ferroelectric varactor (as shown in figure 1), such that the large varactor capacitance at zero bias shunts the input signal to ground, thus isolating the output port, resulting in the OFF state of the device. When one applies a bias voltage of approximately 10 V, the varactor capacitance is reduced to a minimum, allowing most of the signal from the input to be transmitted to the output, thus resulting in the ON state of the device. In figure 1, the top view shows the Ground-Signal-Ground of the CPW in the top metal [metal2]. A portion of the bottom metal (metal1) shunt line is seen as the darker line. The overlap area of the center conductor of the CPW in metal2, and the shunt line in metal1 defines the varactor area. In this work, varactor shunt switches of different sizes were experimentally measured and the electrical device parameters were extracted.

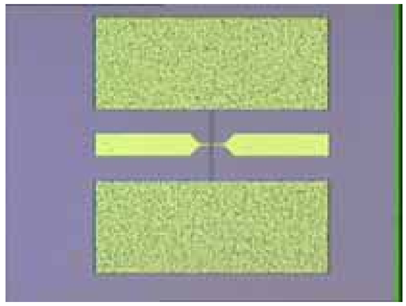


Figure 1. Photograph of a varactor shunt switch. The overlap area of the center conductor in metal2, and the shunt line in metal1 (visible as a darker line) forms the varactor. BST thin-film is coated on the entire surface on top of the patterned metal1 layer.

II. DESIGN

The capacitive shunt switch is designed using coplanar waveguide (CPW) transmission lines on a high resistivity Si substrate (> 6 kΩ) with a thin SiO_2 isolation layer. The thickness of the substrate and SiO_2 layer were 500 μm and 0.3 μm respectively. The design of the ferroelectric varactor shunt switch has been reported previously [5-6]. In this study, we designed and fabricated devices with different varactor area, ranging from 5x5 μm^2 to 17.5 x 17.5 μm^2. CPW Ground-Signal-Ground dimensions were 150μm/50 μm/150 μm on the high resistivity silicon substrate for obtaining a characteristic impedance close to 50 ohms over the range of dielectric tunability.. The overall length of each switch is 500 μm, and the width, 450 μm.

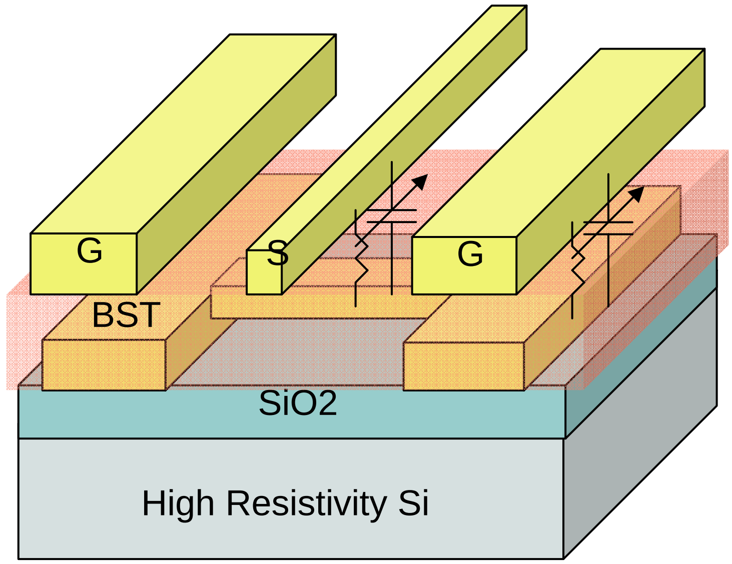


Figure 2. Three dimensional view of the varactor shunt switch showing the varactor and the large ground-pad capacitance.

A three dimensional view of the device is shown in figure 2. The device requires two metal layer process with the BST layer between the metal1 and metal2 layers. The metal2 layer contains the probe-able CPW line for on-wafer probe measurements. Both metal1 and metal2 layers contain the ground lines, as shown in figure 2, resulting in large ground-pad capacitors due to the sandwiched BST layer. In addition, metal1 layer contains a shunt line connecting the two ground lines. As shown in figure 2, a parallel plate varactor is created between the shunt line in metal1 and the center conductor in metal2 layer. The varactor capacitance is essentially in series with the larger ground-pad capacitance, resulting in an effective capacitance of the varactor. The shunt conductances of the large ground-pad capacitors, as well as the varactor, eliminates any need for via holes, resulting in a simple process.

The important device parameters are (i) the varactor area (overlap area of the metal1 and metal2 layers), (ii) CPW transmission line parameters, (iii) parasitic inductance and resistance of the thin-line shunting to ground in metal1, and (iv) the dielectric properties of the nano-structured BST thin-film.

The varactor shunt switch can be precisely modeled as reported earlier [5, 6]. Figure 3 shows the simple electrical model for the device. The parasitic equivalent series inductance (ESL) and equivalent series resistance (ESR) can be precisely calculated from experimental results as described in section IV.

III. EXPERIMENTAL

In this experimental work, we fabricated BST varactor shunt switches with varactor areas of 5 x 5, 7.5 x7.5, 10x10, 12.5x12.5, 15x15, and 17.5x17.5 μm^2 on a single high resistivity Si chip with a 300 nm SiO_2 layer. Standard positive photoresist lift-off photolithography was used for the metal1 layer with a Ti adhesion layer (20 nm) deposited first followed by 800 nm of gold and 100 nm of Pt in an e-beam evaporation system. After the metal1 layer was defined, the $Ba_{0.6}Sr_{0.4}TiO_3$ thin-film was deposited on the entire surface in a process controlled pulsed laser deposition system. The fabrication process for the nano-structured BST thin-films is described else-where [7]. After the BST deposition, the metal2 layer (~ 1 μm) was defined and processed using the positive photoresist lift-off technique to complete the device fabrication. The varactor shunt switches were tested using a HP 8510 Vector Network Analyzer (VNA), with a Line-Reflect-Reflect-Match (LRRM) calibration done over a wide frequency range (5 to 45 GHz). The samples were probed using standard GSG probes, with the dc bias applied through the bias tee of the VNA.

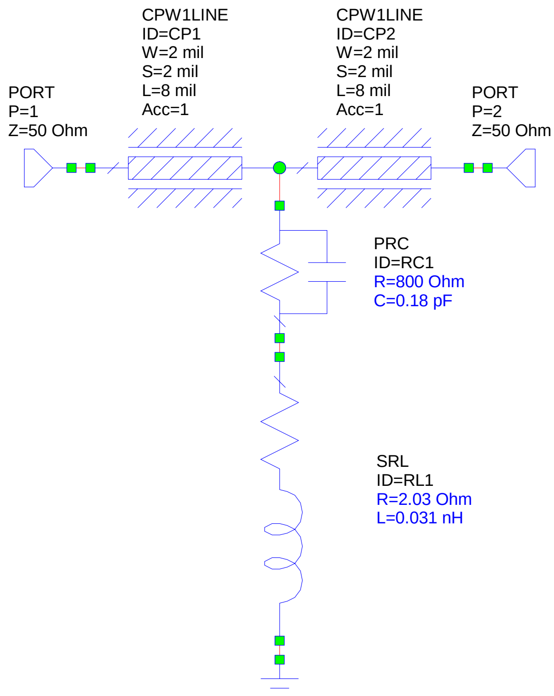


Figure 3. Electrical model for the varactor shunt switch. The values shown are for the 5 x 5 μm^2 device at 12 V dc bias.

IV. RESULTS AND DISCUSSIONS

Experimental results were obtained on several switches with different size (area) of the varactors, fabricated on a single chip. Important observations from the measurements were: 1. Smaller the device area, lower the insertion loss of the devices, and lower the isolation at the zero-bias resonance frequency, as predicted by Sonnet em simulation results. 2. Smaller the device, the higher the breakdown voltage, and 3. Smaller the device, better the impedance matching with bias, over the frequency range of measurements.

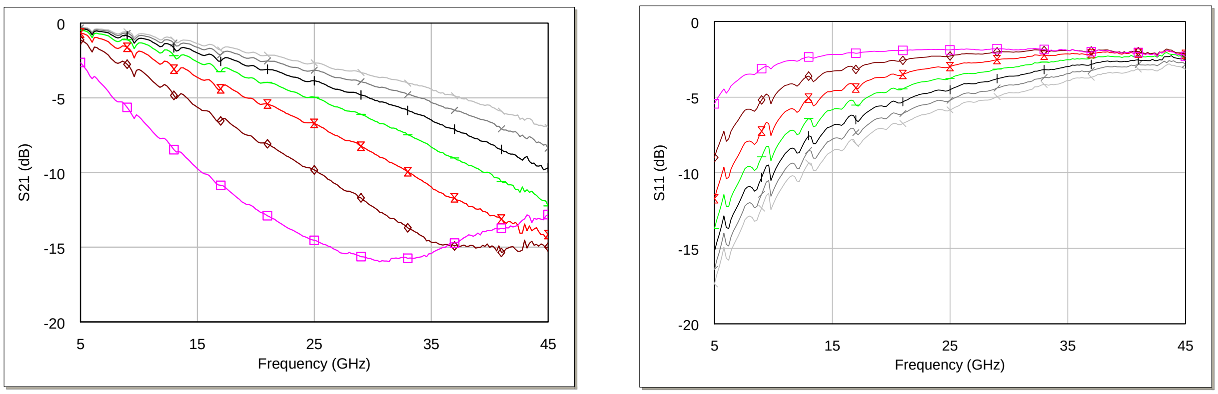


Figure 4. The experimental swept frequency S21 and S11 for a 5x5 um2 varactor shunt switch for 0V (pink) to 12 V (grey) with a step size of 2 V.

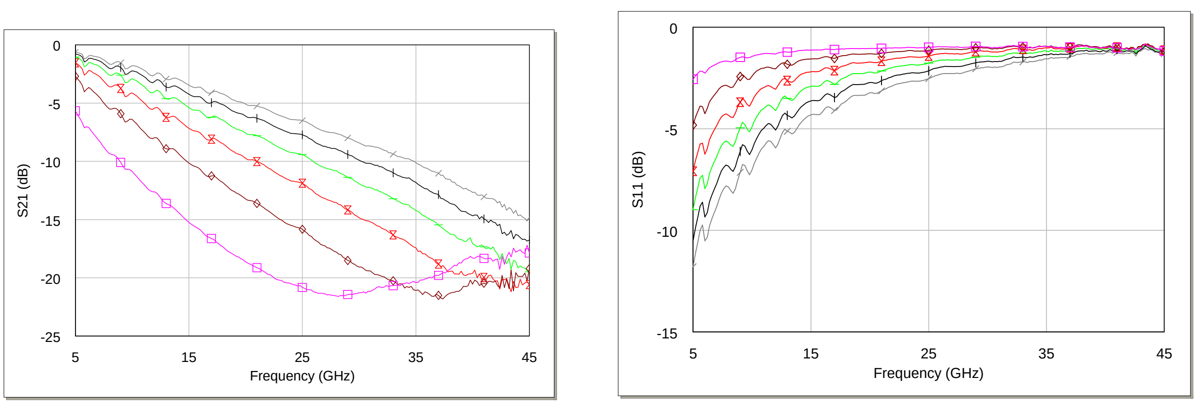
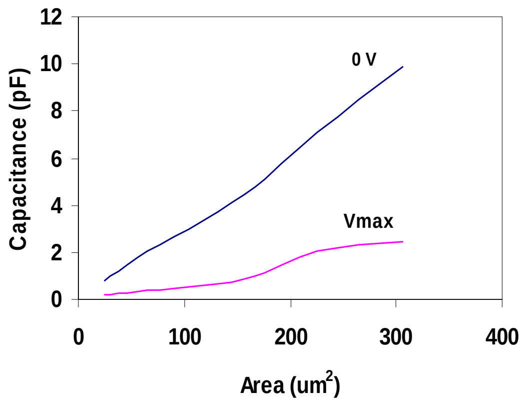


Figure 5. The experimental swept frequency response for a 7.5 x 7.5 um2 varactor shunt switch for 0V (pink) to 10 V (grey) with a step size of 2 V.

Figures 4 and 5 show the experimental swept frequency response of 5 x 5 μm^2 and 7.5x7.5 μm^2 devices respectively for bias voltages 0 V to 12 V with a step-size of 2 V. For the 5x5 μm^2 device, the insertion loss is ~3 dB at the zero-bias resonance frequency of 32 GHz. The isolation of the switch was only ~16 dB at the zero-bias resonance frequency. The 7.5 x 7.5 μm^2 device showed improved isolation at the expense of higher insertion loss. Isolation higher than 30 dB was achievable with device area larger than 100 μm^2, with the insertion loss above 10 dB.



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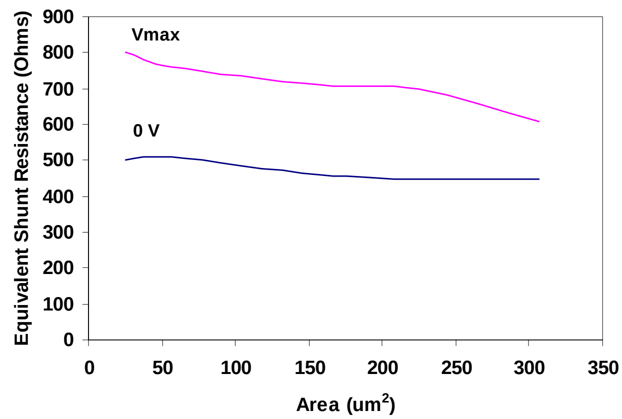

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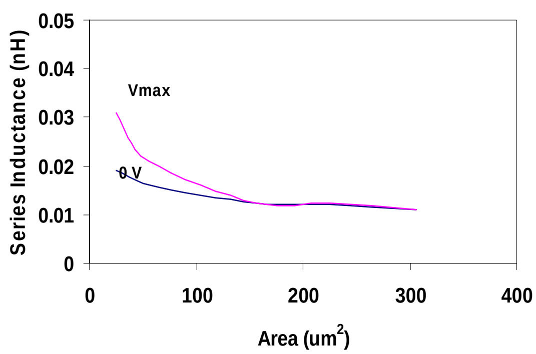

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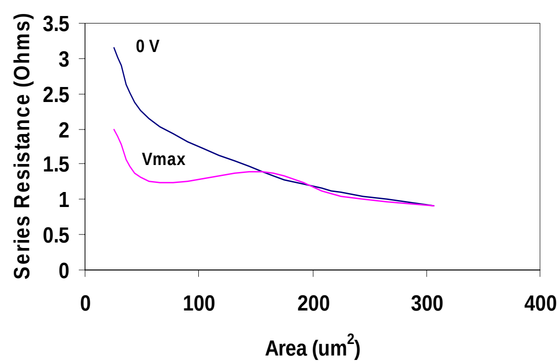


(d)

Figure 6. The electrical parameters extracted for the varactor shunt switches, by comparing the response of the electrical model to the experimental swept frequency data.

Note that the process variation in the BST film deposition on this chip was very high as we processed a larger area of 2x1 inches for the first time. Prior to this run, we had done only samples with an area less than 1 square inch. Higher capacitances were obtained for all of the varactors due to both thickness and process variations over the larger sample, as compared to our prior published work [6].

Using the electrical model shown in figure 3, the electrical parameters of the varactor shunt switches were extracted, by matching the swept frequency response of the modeled circuit to the experimental swept frequency response, using AWR's Microwave Office. Figure 6 summarizes the size dependence of the electrical parameters of the devices as a function of dc bias voltages. Note that each of the devices was subjected to a different maximum bias voltage based on a leakage current criteria of 25 μA. Hence, a generalized Vmax is used for the figure 6. Vmax was 12 V for 5 x 5 μm^2 devices, and was only 8 V for 17.5 x 17.5 μm^2 devices. The capacitance tunability for the devices tested was higher than 4:1 for all of the devices. For the smallest device, the 5 x 5 μm^2, the capacitance at zero-bias was ~0.8 pF, and reduced to 0.18 pF at 12 V. For the largest device, 17.5x17.5 μm^2, the capacitance at zero-bias was 9.86 pF, and reduced to 2.46 pF at 8 V. The equivalent shunt inductance (ESL) for the smaller devices increased with the increasing bias voltage as shown in figure 6.c. Since the self-inductance of a line is independent of the size of the capacitor, and does not change with the properties of the dielectric, the spreading inductance due to the conduction current in the dielectric layer could be contributing to the higher ESL at higher bias voltages, especially for the smaller devices [8]. The equivalent series resistance (ESR) was also bias dependent, and reduced with bias voltage as shown in figure 6.d. for the smaller devices, possibly due to the increasing shunt resistance with bias. For the larger devices, the leakage conduction currents are significantly higher to start with, and results in less of a bias dependence for the ESR and ESL.

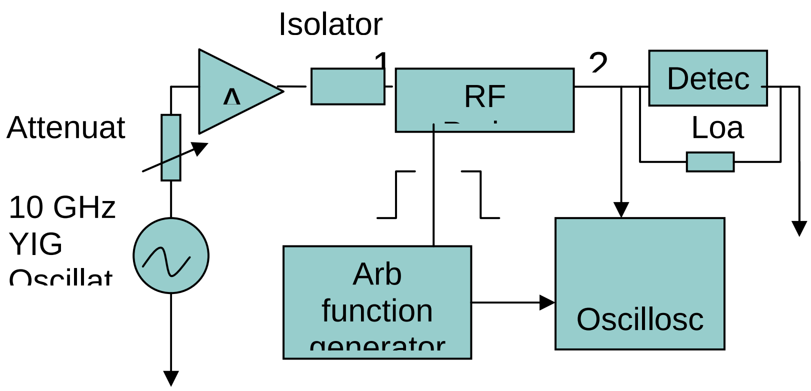
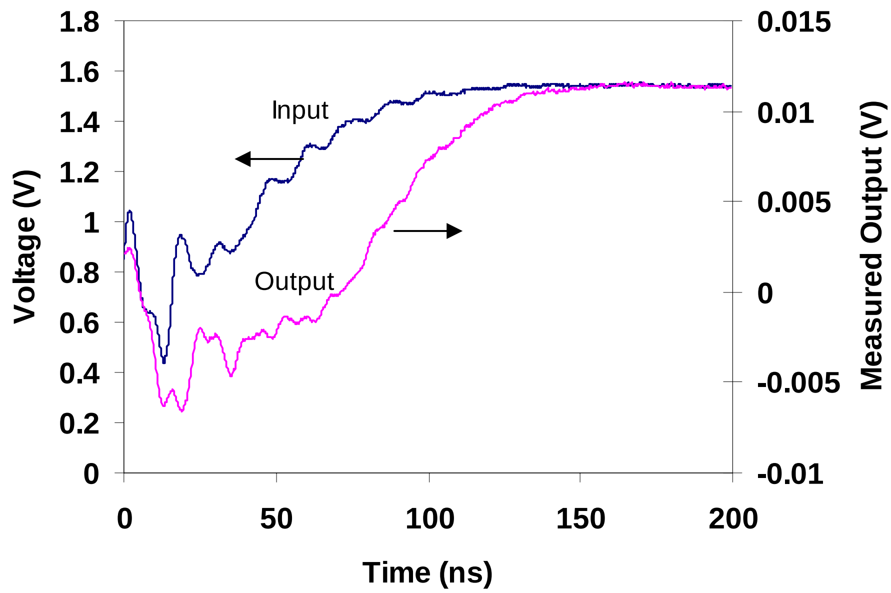


Figure 7. Experimental set up for switching speed measurements

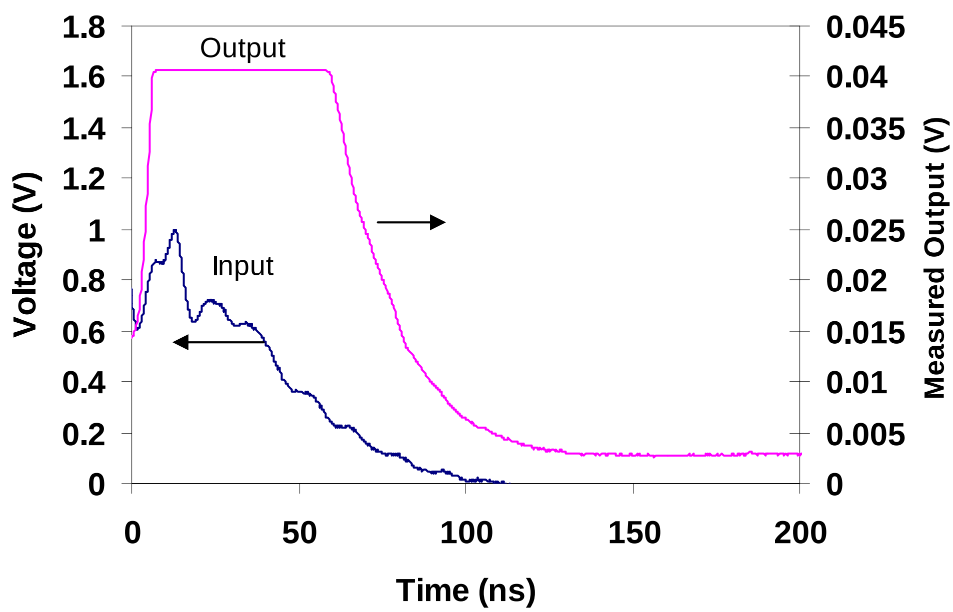
The switching speed of the varactor shunt switches were tested using a continuous wave (CW) microwave signal and a dc step input to obtain both rise and fall times for the switches. The measurement set up for the step response characterization is shown in figure 7. 10 GHz CW microwave signal was generated using a YIG oscillator. The output power was measured using a calibrated diode detector. A thru line calibration was performed before the device was tested. The figure 8 shows the step response of the input (with the thru) and output (with the device) for a 5 x 5 μm^2 varactor shunt switch. The actual device's rise time or fall time is obtained from the following [9]:

$$t_{device} = [t_{input}^2 - t_{output}^2]^{1/2}$$

The rise and fall times for the devices were estimated to be below 50 ns.



(a)



(b)

Figure 8. Measured step response for rise time and fall time of a 5x5 μm^2 varactor shunt switch.

V. SUMMARY AND CONCLUSIONS

Experimental results were obtained on BST based varactor shunt switches of different size, for RF performance evaluation and electrical parameter extraction. Devices tested were fabricated on a single high resistivity Si substrate. All the devices tested, showed capacitance tunability of more than 4:1 for a dc bias voltage below 12 V. The electrical parameter extraction showed that the equivalent series resistance (ESR) and equivalent series inductance (ESL) were bias dependent for the smaller devices. The switching speed of the devices was estimated to be approximately 43 ns. Improvements to the device design are currently underway for lower insertion loss and higher isolation. Low loss and high isolation ferroelectric varactor shunt switches are promising for various applications including reconfigurable circuits.

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REFERENCES

[1] C.H.Mueller, and F.A.Miranda, “Tunable Dielectric Materials and Devices for Broadband wireless communications”, in *Ferroelectric and Acoustic Devices*, Eds: D.Taylor, and M. Francombe, Academic Press, 2000.

[2] R.York, A. Nagra, E. Erker, T.Taylor, P. Periaswamy, J. Speck, S. Streiffer, and O. Auciello, ”Microwave integrated circuits using thin-film BST”, Proc. 12th IEEE Intl . Applications of Ferroelectrics Symp., vol.1, pp.195-200, 2001.

[3] A. Tombak, J-P. Maria, F. Ayguavives, Z. Jin, G.T. Stauf, A. I. Kingon, and A. Mortazawi, “ Tunable barium strontium titanate thin film capacitors for RF and microwave applications”, IEEE Microwave and Wireless Comp. Lett.., vol.12, pp. 3-5, Jan 2002.

[4] A. Vorobiev, P. Rundqvist, and K. Khamchane, and S. Gevorgian, et al., “Silicon substrate integrated high Q factor parallel plate ferroelectric varactors for microwave/millimeterwave applications”, Applied Physics Letters, vol.83, no.15, pp.3144-46, 2003.

[5] F. Ahamed and G. Subramanyam, “Design of a Si MMIC compatible ferroelectric varactor shunt switch for microwave applications”, presented in the IEEE Ultrasonics Ferroelectrics and Frequency Control Symposium, Montreal, Canada, August 2004.

[6] G. Subramanyam, F. Ahamed, R. Biggers, A. Campbell, R. Neidhard, E. Nykiel, R. Cortez, K. Stamper, and M. Calcatera, “A new ferroelectric varactor shunt switch for microwave and millimeterwave reconfigurable circuits”, Frequenz Journal, vol.59, 1-2, February 2005.

[7] B. Riehl, G. Subramanyam, R. Biggers, and A. Campbell, F.W.Van Keuls, F.A. Miranda, and D. Tomlin,“Synthesis and characterization of nano- structured BST thin-films for microwave applications,” Integrated Ferroelectrics, vol. 55, pp. 825-837, 2003.

[8] Y. Zhou, R. Wenzel, and B.Herberg, “Modeling the intrinsic inductance of embedded capacitors”, Proceedings of the IEEE Electronic Components and Technology Conference, pp. 167-170, 2002.

[9] K. Honjo, and Y. Takayama, “GaAs FET ultra-broadband Amplifiers for Gbit/s Data Rate Systems”, IEEE Trans MTT, vol. MTT-29, pp. 629-636, 1981.